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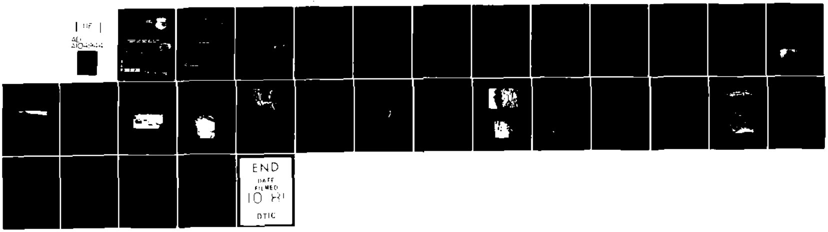

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# MORPHOLOGY AND HISTOLOGY OF SPINAL LIGAMENTS FROM THREE PRIMATES

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report covers a study of the histological and morphological features of four spinal ligaments. Gross and microscopic characteristics of the anterior and posterior longitudinal ligaments, ligamentum flavum and supraspinous ligaments were observed at varying vertebral levels and compared between rhesus monkey, baboon and chimpanzee. Information on the properties of the spinal ligaments is essential to understanding the mechanism of spinal injuries observed in aircrewmen under emergency egress from aircraft as well as under routine high performance flight conditions. Knowledge about the different primate species will aid

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in the selection of animal models for human injury testing and interspecies scaling techniques.

## SUMMARY

This report defines morphological and histological features of four spinal ligaments from three primate species. The data will serve to formulate structural models for mechanical studies being conducted concurrently.

Two stains, specific for collagen and elastin, were used to indicate microscopic fibrous composition. The histological sections were selected to show fiber size, orientation and mode of attachment. These sections allowed observation of changes in the ligament and bone geometries.

The observations recorded in this study show a significant similarity of histological features between species and throughout the vertebral column. Morphologically it was seen that substantial geometric differences existed between vertebral levels and species. Some of these differences are tabulated in this report. The data gathered here yield information needed in the mechanical studies of the spinal ligaments. The combined mechanical, morphological and histological studies of the spinal ligaments are necessary to understand the mechanism of spinal injuries observed in aircrews under emergency egress conditions as well as routine high performance flights. Information on the different primate species will aid in the selection of animal models for human injury tests and of interspecies scaling techniques for predicting spinal response to various deformations or loads.



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# PREFACE

This study was conducted in the Department of Biomechanics, College of Osteopathic Medicine, Michigan State University, East Lansing, Michigan 48824, under AF Contract No. F33615-79-C-0514. Dr. Robert Wm. Little, Professor and Chairman of the Department, was the Principal Investigator. Mr. David L. Hyler, the senior author, and Ms. Jane A. Walsh were also members of the Department of Biomechanics. This investigation, part of a three-year effort, supported Work Unit 7231-14-09, "Mechanical Stress on Soft Tissue Material Properties." Dr. Arnold R. Slonim of the Biodynamic Effects Branch, Biodynamics and Bioengineering Division, Air Force Aerospace Medical Research Laboratory, was the project scientist and contract monitor.

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Morphology and Histology of Spinal Ligaments
from Three Primates

## INTRODUCTION

The work reported here is in support of mechanical studies of primate spinal ligaments conducted in the Department of Biomechanics at Michigan State University as a joint effort with the Air Force Aerospace Medical Research Laboratory (AFAMRL). It is clear that there is an intimate relationship in tissues between structure and function. With this in mind, this study was undertaken to discern histological and morphological features of four spinal ligaments in primates. This study examines the comparative features of supraspinous ligament (S.S.L.), ligamentum flavum (L.F.), anterior longitudinal ligament (A.L.L.), and posterior longitudinal ligament (P.L.L.) from different vertebral levels of rhesus monkey, baboon and chimpanzee.

Of specific interest are: 1) the orientation of the fibrous components; 2) the attachment locations of fibrous structures to bone; 3) the composition of fiber bundles, i.e., elastic fibers, collagen and loose connective tissue; 4) the distribution of fibers; 5) the pre-existing tensions in the fibers, observed by the amount of "waviness" in the fiber bundles and the geometric size variation; and 6) the question of the existence of S.S.L. in the lower lumbar region.

The aim of this report is to present a comparative overview of these ligaments and no attempt has been made to cite all available literature. Extensive bibliographies can be found pertaining to the surgical anatomy of some of these ligaments in humans (3,4,15). Literature on the morphology of individual ligaments in humans arose from surgical and pathological considerations, and most of this information is centered on ligamentous structures at cervico-thoracic or thoraco-lumbar junctions. Little work has been done to meet the specific needs of a mechanical study as cited above.

## METHODS AND MATERIALS

Samples of spinal ligaments were taken from rhesus monkeys, baboons, and chimpanzees which had not been subjected to any prior experimentation and which were supplied by AFAMRL. Carcasses were received in a chilled state within twenty-four hours of sacrifice.

The spine was surgically removed and segmented immediately upon arrival, as described by Little and co-workers (10). Special care was taken not to disrupt the ligamentous structures, and dissection was performed in a humid atmosphere to prohibit desiccation of specimens. Segments for use in future mechanical studies were frozen at -5°C. From the seven rhesus monkeys, samples for histology were taken at T2, T5, T11, L4 and L7; from the three baboons, samples were taken at T2, T5, T11, L4 and L7; and from the three chimpanzees, samples were taken at T2, T5, T8, L2 and L5.

Specimens were immediately fixed in 10% buffered formalin for several days. This was followed by decalcification in D-calcifier (Lerner Laboratories) for one-to-three days, depending on size. Samples then were cut in serial longitudinal and transverse sections (longitudinal and transverse sections referred to here are relative to the geometry of individual vertebral bodies). The transverse sections were perpendicular to the axis of the cylindrical body, and the longitudinal

sections studied here were restricted to mid-sagittal sections. The transverse sections studied ranged from those taken mid-body to those taken at the end of the body. Care must be taken in orienting these sections with regard to the entire in vivo spine since the effect of overall spinal curvature was lost when the vertebral body was removed from the spine. Sections were selected to include sites of bony attachments and to allow the determination of the orientation of fibrous components in axial or transverse directions. These sections also provided information as to the distribution of fiber attachments along the body.

After fixing, samples were processed through a routine paraffin embedding method, cut at 7μ thickness on a rotary microtome and stained. Routine staining procedures do not ordinarily identify some specialized tissue components, thus selective staining techniques must be used (1). Stains used in this study were Hematoxylin-Eosin (11) for general morphology, Davenport's modification of Halmi (2) for collagen and elastic fibers, and Fraenkel's Orcein (9) for elastic fibers.

## OBSERVATIONS

Typical Vertebral Geometry:

The anatomical geometry of the vertebrae has been described in the literature by Swindler and Wood (1973), Kapandji (1974), Hamilton (1976), Gray (1977) and Kazarian (1978). Although variations are seen in the geometric features of different vertebrae, a typical vertebra consists of two components, the vertebral body and the vertebral arch. The vertebral body constitutes the largest part of the typical vertebra. The body is a tapered cylinder being wider than it is tall. The anterior surface shows a marked concavity, and the posterior is relatively flat between the pedicles. The degree of the concavity is illustrated by the variation in the anterior-posterior thickness measurements of the vertebral body as presented in Table 1.

The vertebral arch is horseshoe-shaped and can be divided into two parts, the short stout pedicles arising from the body and posterially the lamina. The lamina from both sides meet mid-sagittally to form the spinous process, which extends posterio-caudially and terminates with a single tubercle at its tip.

Ligamentum flavum (L.F.):

The ligament proper consists of two sagittally-symmetric lobes separated by a loose connective tissue layer. Yellowish in appearance and highly elastic in nature, it inserts inferiorly into the superior border of the lower lamina. It courses over the interlaminar space and inserts superiorly into the medial aspects of the upper lamina. Laterally, the ligament thins out and becomes continuous with the capsular and anteriomedial ligaments of the joints between the articular facets. Dorsally, the L.F. becomes continuous with the interspinous ligament (I.S.L.) which runs dorso-cranially from the base of the spinous process at the neural arch to the next process. Compositionally, there is no distinct border between the L.F. and I.S.L. The criterion used here to distinguish the posterior border of the L.F. was fiber direction. Approaching the base of the process at the neural arch, the fiber orientation changes from predominately axial between two adjacent lamina to a markedly dorso-cranial direction as the fibers begin to span from one process to the next.

Microscopically, the L.F. is observed to be composed of tightly compacted, thick

TABLE 1. VERTEBRAL BODY GEOMETRY

| | | Height* | Thickness at Disc** | Thickness Mid-body | Cross-Sectional Width at Center+ | Central Cross-Sectional Area++ |
|---|---|---|---|---|---|---|
| Rhesus | T2 | 4.5 mm | 6.3 mm | 5.0 mm | 9.0 mm | 37.0 $mm^2$ |
| | T5 | 7.4 | 7.0 | 5.5 | 9.5 | 52.0 |
| | T11 | 9.3 | 10.5 | 9.2 | 11.0 | 94.0 |
| | L4 | 10.0 | 12.5 | 9.8 | 26.5 | 191.0 |
| Baboon | T2 | 8.1 | 11.3 | 9.5 | 12.2 | 106.0 |
| | T5 | 11.0 | 12.0 | 10.0 | 12.3 | 109.0 |
| | T11 | 14.0 | 14.4 | 13.8 | 18.4 | 211.0 |
| | L4 | 15.5 | 19.5 | 14.0 | 29.1 | 283.0 |
| Chimpanzee | T2 | 11.6 | 14.2 | 13.0 | 20.5 | 175.0 |
| | T5 | 16.0 | 16.3 | 15.7 | 21.0 | 213.0 |
| | T8 | 18.8 | 20.4 | 17.6 | 22.6 | 306.0 |
| | L2 | 28.4 | 28.5 | 22.5 | 28.5 | 626.0 |

*Height represents distance between cartilagenous end plates.

**Thickness measurements were taken mid-sagitally from most anterior point to most posterior point.

+Width measurement taken from inner edge of one pedicle to inner edge of other.

++Cross-sectional areas were obtained by using a calibrated photographic enlargement of histological slides and a Neumonics digitizer.

elastic fibers with small amounts of collagen interspersed between. Nachemson and Evans (15) reported that this ligament has a collagen composition of 30 to 40 percent dry weight, but microscopic observations indicate that the collagen content here may be lower than this. At the bone-ligament interface, there occurs a zone of collagenous fibers which attach at varying angles to the striations of the laminar bone (Fig. 1). The elastic fibers arise within this collagenous zone and become compacted at the outer edge of the collagen (Fig. 2). The presence of this zone was also noted by other investigators, e.g., Nunley (14) and Serafini-Fracassini et al. (16). These elastic fibers are thick and axially directed and course parallel to each other. The lateral postion (capsular) shows a higher collagen content; the fiber orientation is less well-organized than the interlaminar portion; and the fibers are skewed from the axial direction. The fibers, although fairly straight, tend to show a variance in waviness at the elastic-collagen interface between specimens and between vertebral levels. It is believed that this waviness is a result of the release of tension in the fibers upon dissection (14).

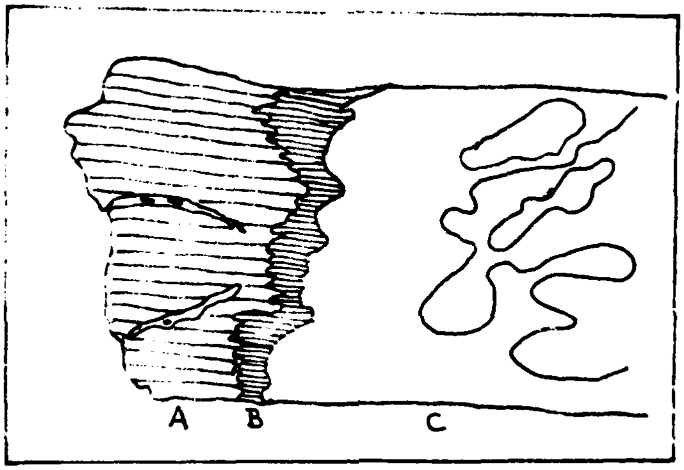


Figure 1: Schematic Illustration of L.F. - Longitudinal Section: (A) Compact Elastic Fibers; (B) Collagenous Zone of Attachment; (C) Bone.

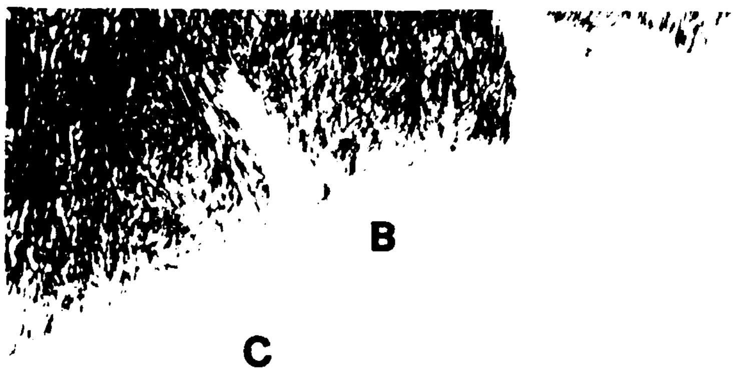


Figure 2: L.F. - Longitudinal Section - Chimpanzee (T8): (A) Elastic Fibers; (B) Collagenous Zone; (C) Bone.

This ligament is microscopically similar at different vertebral levels and in different species. Nominal geometric differences do occur at different levels and in different species as seen in Table 2.

Posterior Longitudinal Ligament (P.L.L.):

Situated centrally on the posterior aspect of the vertebral body, the P.L.L. has an hour-glass configuration as it courses over the bone. It is a bilaterally symmetric structure with the inferior-superior symmetry subject to the taper of the vertebral bodies. The geometry of this basic shape varies with vertebral level and species. The ligament reaches its narrowest dimension mid-body and broadens out to cover the entire posterior aspect of the intervertebral disc. The ligament at mid-body is often not attached to the bone leaving a free space often traversed by vascular structures, as seen in Fig. 3 (7). Fiber attachments increase in number as the ligament approaches the cartilagenous end plates. The vast majority of fibers insert into the end plate or interweave with the fibers of the annulus fibrosus as they cross the disc space.

Figure 3: P.L.L. at Mid-body Unattached to Bone - Cross-Section - Baboon (T11).

Microscopically the ligament is observed as a three-layered structure (Fig. 4). The thin inner portion (adjacent to the bone) is a network of fine collagenous fibers whose distribution of attachment to the bone vary according to vertebral level and species. This layer often extends into the marrow spaces and attaches to inner bony spicules (12). Those fibers with superficial attachments have consistent orientation with the striations of the bony surface. Fine fibers from the inner layer extend out to the middle layer and contribute to the composition of the larger fiber bundles seen there (Fig. 5).

TABLE 2. LIGAMENTUM FLAVUM GEOMETRY

| | | Central Anterior-Posterior Thickness* | Central Lateral Width** | Central Cross-Sectional Area+ |
|---|---|---|---|---|
| Rhesus | T2 | 3.6 mm | 6.0 mm | 17.0 $mm^2$ |
| | T5 | 3.8 | 7.0 | 20.0 |
| | T11 | 4.7 | 8.0 | 20.0 |
| | L4 | 5.75 | 15.0 | 35.0 |
| Baboon | T2 | 3.85 | 5.0 | 25.0 |
| | T5 | 7.25 | 5.2 | 34.0 |
| | T11 | 8.25 | 10.2 | 94.0 |
| | L4 | 9.1 | 13.4 | 78.0 |
| Chimpanzee | T2 | 2.5 | 7.0 | 16.0 |
| | T5 | 3.25 | 8.0 | 18.0 |
| | T8 | 4.25 | 10.2 | 24.0 |
| | L2 | 8.25 | 16.0 | 50.0 |

*Anterior-posterior thickness represents the distance from the most anterior apex of the curvature of both lobes to the posterior border of the ligament.

**Lateral width represents the greatest distance between the two lateral edges of the interlaminar portions.

+Cross-sectional areas were obtained by using a calibrated photographic enlargement of histological slides and a Neumonics digitizer.

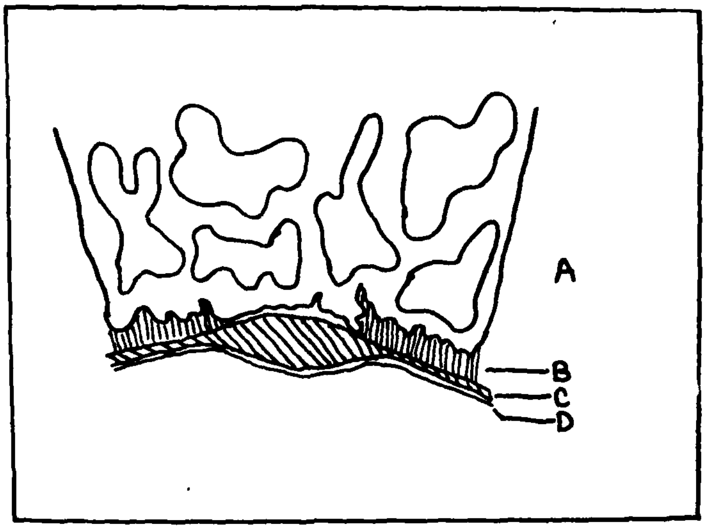


Figure 4: Schematic Illustration of P.L.L. - Cross-Section Near Vertebral Edge: (A) Bone; (B) Collagenous Zone; (C) Middle Layer; (D) Outer Layer.

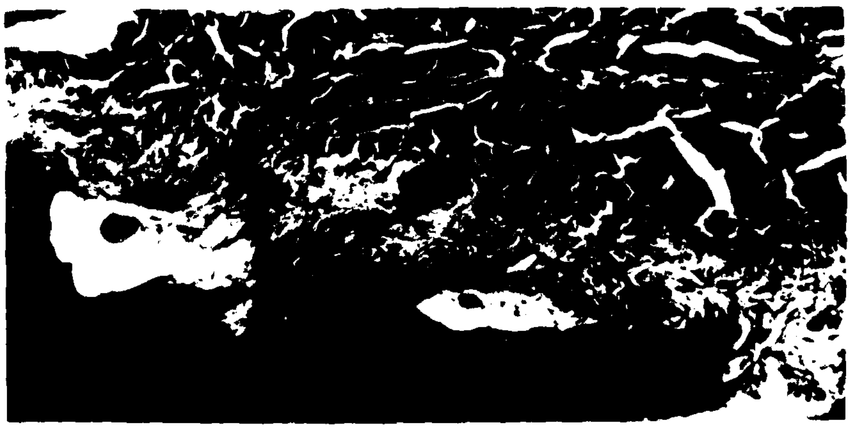

Figure 5: P.L.L. - Distribution of Fibers of Inner Layer - Cross-Section Near Vertebral Edge - Baboon (T8): Zone of Fine Fibers and Collagen Attaching to Bone and Larger Fiber Bundles.

The middle layer, composed of these larger bundles, constitutes the major portion of the ligament. In addition to the fiber attachments observed in the inner portion, it was seen that some larger fiber bundles from the middle layer insert into the cartilage end plate of the vertebral body (Fig. 6). Others course over the disc space, interweaving with fibrous bands of the annulus fibrosus (Figs. 7 & 8).

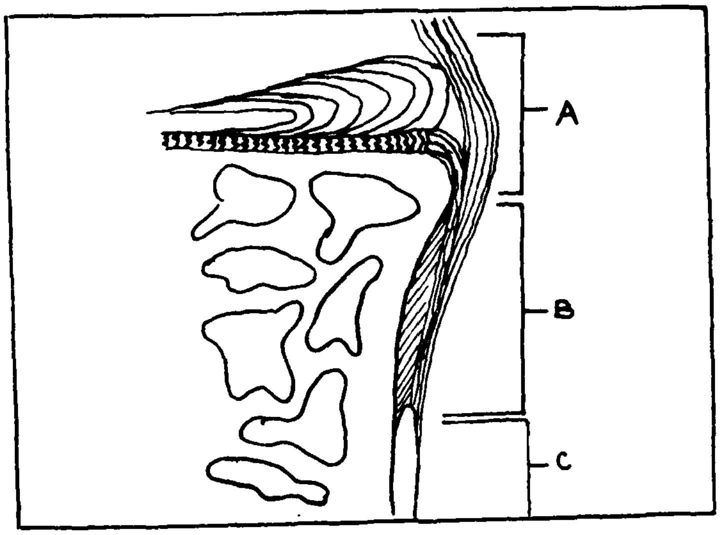


Figure 6: Schematic Illustration of P.L.L. - Longitudinal Section: (A) Fibers Inserting Into Cartilage End Plate and Coursing Over the Annulus Fibrosus; (B) Fibers and Collagenous Zone of Attachment; (C) Zone of Detachment from Vertebral Body.

Figure 7: P.L.L. - Middle Layer Fibers - Longitudinal Section - Rhesus Monkey (L4): Middle Layer Fibers Coursing Into Cartilage Plate and Outer Layers Coursing Over Disc Area.

Figure 8: P.L.L. - Middle Layer Fibers - Longitudinal Section - Baboon (L7): Fibers Coursing into Cartilage Plate and Over the Disc Space.

At the mid-sagittal line the fibers run axially, along the geometric contours of the vertebral body. From the mid-sagittal plane, the ligament fans out laterally and the fibers course at various angles from this plane so as to cover the entire posterior portion of the disc. As the ligament flares out over the mid-portion of the body, the fibers are seen to interweave, particularly on the periphery. The ligament courses across the disc space along the entire posterior aspect of the body. The attachments at the cartilage end plate provide the major anchor points for the ligament to the bone. The interweaving of ligamentous fibers with those of the annulus fibrosus constitutes a strong bond which makes surgical separation much more difficult than the A.L.L. The fibrous components of the ligament are collagenous with significant amounts of vascularization seen along the lateral aspects. Elastic fibers are evident in varying amounts.

The outer area consists of loose connective tissue whose fibers are randomly oriented and appear to be of a minimum structural importance. It can be postulated that this layer acts as a frictional buffer zone between ligamentous surface and adjacent structures (19). Table 3 presents the findings observed for P.L.L.

Anterior Longitudinal Ligament (A.L.L.):

The anterior longitudinal ligament is a broad bilaterally symmetric fibrous band which courses over the contoured surface of the vertebral bodies. Basically a parallel-fibered structure, it does have numerous fibers which intermingle with the periosteum of the vertebral bodies and the annular fibers of the intervertebral discs, thus yielding a complex meshwork. Its circumferential

TABLE 3. POSTERIOR LONGITUDINAL LIGAMENT GEOMETRY

| | | Anterior-Posterior Thickness-Mid-Body* | Anterior-Posterior Thickness-Disc | Central Lateral Width | Central Cross-Sectional Area† |
|---|---|---|---|---|---|
| Rhesus | T2 | 0.6 mm | 0.5 mm | 3.0 mm | 2.0 $mm^2$ |
| | T5 | 0.4 | 0.3 | 3.0 | 2.2 |
| | T11 | 0.6 | 0.3 | 4.0 | 5.5 |
| | L4 | 0.5 | 0.4 | 6.5 | 3.5 |
| Baboon | T2 | 0.8 | 0.4 | 5.8 | 4.0 |
| | T5 | 0.9 | 0.6 | 8.5 | 8.0 |
| | T11 | 0.9 | 0.7 | 9.1 | 6.0 |
| | L4 | 0.9 | 0.6 | 10.1 | 7.5 |
| Chimpanzee | T2 | 0.7 | 0.4 | 8.0 | 5.0 |
| | T5 | 1.0 | 0.5 | 6.0 | 4.0 |
| | T8 | 1.0 | 0.8 | 9.0 | 5.0 |
| | L2 | 1.9 | 1.5 | 10.1 | 6.5 |

*Anterior-posterior measurements represent the distance from posterior to anterior surfaces of the ligament.

†Cross-sectional areas were obtained by using a calibrated photographic enlargement of histological slides and a Neumonics digitizer

extensions over the bony surface vary at mid-body from a narrow band in certain specimens to a broad cylindrical band extending over the entire surface in others. As it approaches the ends of the vertebral body, the ligament broadens out to cover the entire circumferential border, pedicle to pedicle. The thickness diminishes laterally from the mid-sagittal plane. Unlike the P.L.L., the A.L.L. rigidly adheres to bony surface over its entire length. Table 4 indicates the dimensions of the A.L.L.

Three fibrous layers are observed (Fig. 9). In the upper lumbar region the diaphragmatic tendon is seen as an additional outer layer, which is inseparable from the ligament. At the bony surface is an inner layer of fine fibers and connective tissue that attaches to the bone (Fig. 10). Within this area are strands of wavy fibers extending outward to contribute to the larger fiber bundles of the middle layer. This inner layer thins as it approaches the cartilage end plate of the vertebral body.

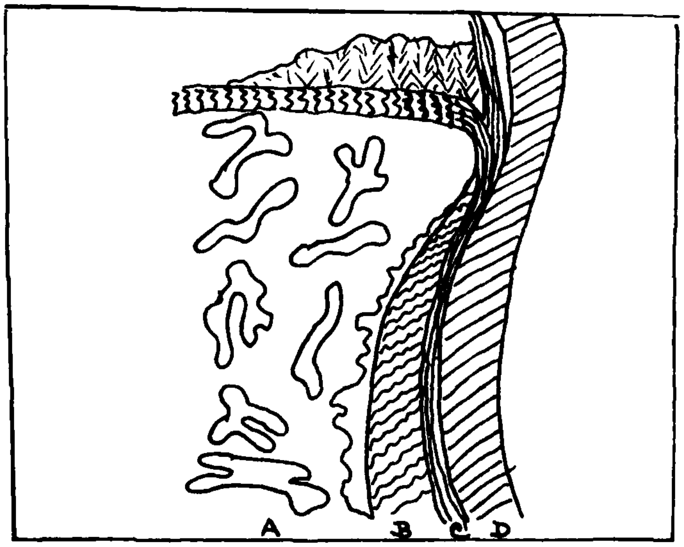


Figure 9: Schematic Illustration of A.L.L. - Longitudinal Section: (A) Bone; (B) Inner Collagenous Zone of Attachment; (C) Middle Fiber Layer Coursing to Cartilage End Plate and Over Annulus Fibrosus; (D) Outer Fiber Layer.

TABLE 4. ANTERIOR LONGITUDINAL LIGAMENT GEOMETRY

| | | Anterior-Posterior Thickness-Mid-Body* | Anterior-Posterior Thickness-Disc | Central Cross-Sectional Area÷ |
|---|---|---|---|---|
| Rhesus | T2 | 0.75 mm | 0.6 mm | 5.5 $mm^2$ |
| | T5 | 1.2 | 1.0 | 11.0 |
| | T11 | 2.25 | 1.6 | 27.0 |
| | L4 | 2.8 | 2.0 | 26.0 |
| Baboon | T2 | 2.2 | 1.0 | 19.0 |
| | T5 | 1.45 | 1.7 | 18.5 |
| | T11 | 2.05 | 2.2 | 27.5 |
| | L4 | 2.4 | 2.4 | 12.0 |
| Chimpanzee | T2 | 1.4 | 0.9 | 23.5 |
| | T5 | 1.9 | 1.5 | 40.5 |
| | T8 | 2.65 | 1.1 | 61.0 |
| | L2 | 3.15 | 1.8 | 60.0 |

*Anterior-posterior measurements represent the distance from the posterior to anterior surfaces of the ligament mid-sagittally

÷Cross-sectional areas were obtained by using a calibrated photographic enlargement of histological slides and a Numonics digitizer.

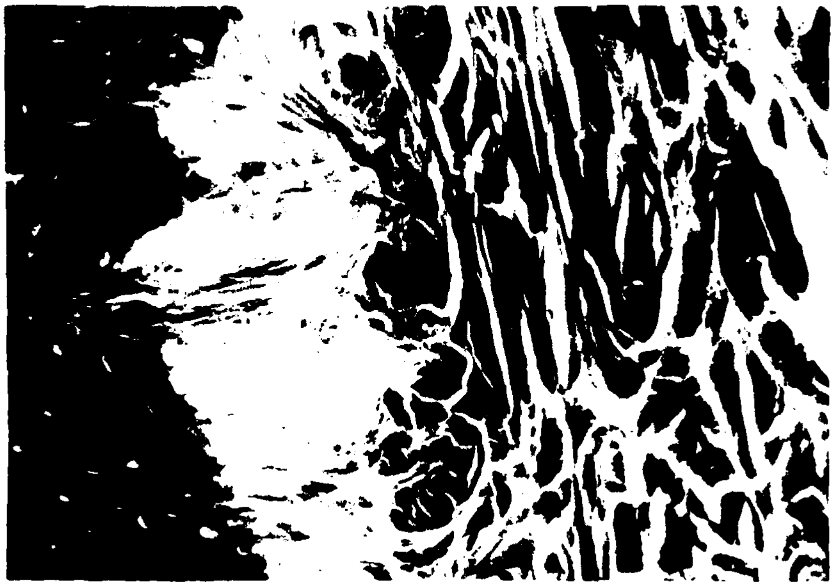

Figure 10: A.L.L. - Inner Layer Fibers - Cross-Section - Chimpanzee (T8): Zone of Collagen and Fine Fibers Attaching Larger Fiber Bundles to Bone.

The middle layer consists of thick parallel fiber bundles running axially along the vertebral body. Numerous fibers insert into the cartilage end plate, while others course over the disc space. These inner fibers are seen to intermingle with the fibers of the annulus fibrosus (Fig. 11). This attachment is not as strong as that of the P.L.L., and surgically it is possible to "shell" the annular rings from the posterior of the A.L.L.

Figure 11: A.L.L. - Longitudinal Section - Rhesus Monkey (L4): Middle Layer Fibers Course Over Disc Area and Inner Fibers Attach at Cartilage End Plate.

The outer fiber layer consists of thick fiber bundles spanning over the disc space predominantly in an axial direction. The fibers are parallel to each other and waviness increases towards the anterior surface of the ligament becoming quite pronounced in the outer layer.

The ligament is composed of dense collagen fibers, with the chimpanzee showing substantial numbers of elastic fibers at all vertebral levels. The elastic composition increases as one proceeds down the spine, lumbar being most heavily populated by elastic fibers.

Supraspinous Ligament (S.S.L.):

In comparison with the three previously mentioned ligaments, the geometry of the S.S.L. is not as well defined. It does, however, display a number of consistant characteristics. It is a three-layered fibrous band which is bordered anteriorly by the interspinous ligament, posteriorly by the lumbo-dorsal facia, and laterally by numerous muscles and their tendinous attachments. The ligament has a varying trapizoidal cross-sectional geometry where it attaches to the spinous process, the narrow base being at the cartilagenous cap. Table 5 respresents some pertinent data for the S.S.L.

The inner fiber layer is the most predominant, and it is composed of thin fiber bundles which attach to the cartilage cap (Figs. 12 & 13). The cartilage cap covers the apex of the spinous process and varies from nearly hemispherical to a flattened oval structure. At the center of the cap, the fibers are almost perpendicular to it and then turn to run tangentially. The angulation of attachments decreases from the perpendicular from the center of the cap. As the fibers course from one process to the next, the fibers intermingle forming the larger bundles of the middle layer.

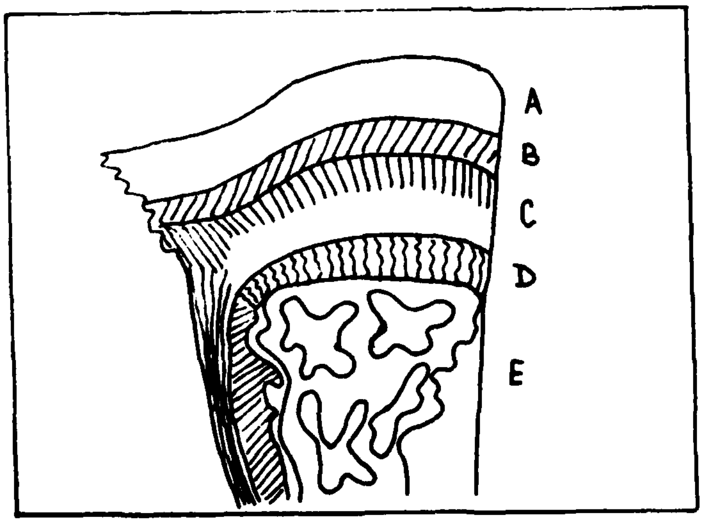


Figure 12: Schematic Illustration of S.S.L. - Longitudinal Section: (A) Outer Layer; (B) Middle Layer of Larger Fiber Bundles; (C) Cartilage Cap with Interwoven Fibers; (D) Cartilage Growth Plate; (E) Bone. Along the left side is the interspinous ligament and its collagenous attachment zone.

TABLE 5. SUPRASPINOUS LIGAMENT GEOMETRY

| | | Central Anterior-Posterior Thickness* | Central Lateral Width** | Central Cross-Sectional Area+ |
|---|---|---|---|---|
| Rhesus | T2 | 0.55 mm | 2.0 mm | 2.0 $mm^2$ |
| | T5 | 0.65 | 2.0 | 3.0 $mm^2$ |
| | T11 | 0.65 | 2.1 | 3.5 |
| | L4 | 0.5 | 3.0 | 4.5 |
| Baboon | T2 | 1.1 | 2.5 | 4.0 |
| | T5 | 1.0 | 2.5 | 3.5 |
| | T11 | 0.95 | 3.0 | 8.5 |
| | L4 | 0.9 | 3.2 | 9.0 |
| Chimpanzee | T2 | 1.05 | 4.5 | 13.0 |
| | T5 | 1.3 | 3.5 | 9.5 |
| | T8 | 1.25 | 4.0 | 16.5 |
| | L2 | 0.95 | 6.0 | 21.0 |

*Anterior-posterior measurements represent the distance from the apex of the cartilagenous cap to the posterior boundary of the ligament.

**Lateral width represents the width of the cartilagenous cap.

+Cross-sectional areas were obtained by using a calibrated photographic enlargement of histological slides and a Numonics digitizer.

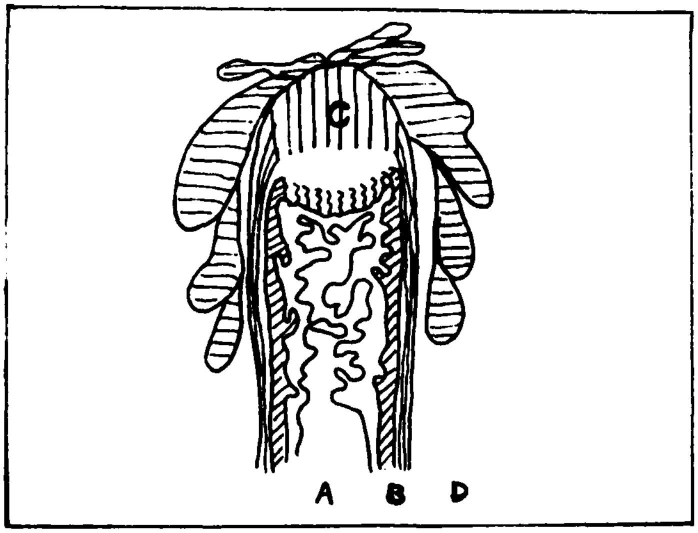


Figure 13: Schematic Illustration of S.S.L. - Cross-Section: (A) Bone; (B) Interspinous Ligament and Attachment Zone; (C) Supraspinous Ligament at Tip of Cartilage Cap; (D) Muscles and Loose Connective Tissue.

This middle layer consists of fiber bundles, intermittently broken up by areas of loose connective tissue and tending to skew anterio-cranially. Numerous disarrayed connective tissue fibers are seen on the periphery together with muscle fibers. These appear to be the remnants of numerous muscles and their tendinous attachments in this area.

The outer tissue layer surrounding the S.S.L. consists of loose connective tissue with much muscle and is in great disarray. This layer seems to be a frictional buffer zone between ligamentous surface, surrounding muscles and lumbo-dorsal fascia, as shown in Figs. 14 & 15 (19).

Figure 14: S.S.L. - Longitudinal Section - Baboon (T11): (A) Cartilage Cap; (B) Interwoven Fibers; (C) Larger Fiber Bundles; (D) Muscle and Loose Connective Tissue.

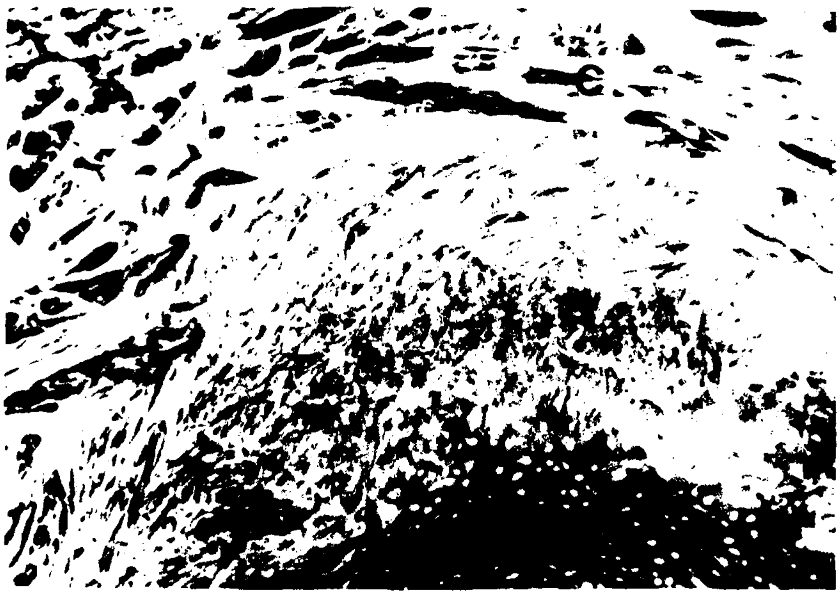

Figure 15: S.S.L. - Cross-Section - Baboon (T2): (A) Cartilage Cap; (B) Inner Fiber Layer, Interwoven at Cap; (C) Middle Layer of Larger Bundles.

## DISCUSSION

Vertebral Geometry:

The vertebrae at all levels resemble the typical vertebra described earlier. Significant alterations appear which affect the geometry of both the body and the arch. These variations of the bony structures, in turn, influence the orientation of the ligaments themselves. The changes in geometry reflecting levels of the vertebrae in the human spine are described well by Gray (3) and Kapandji (7). Similar changes in primates were observed in this study.

Ligamentum flavum (L.F.):

Of all four ligaments studied, the ligamentum flavum showed the least amount of variation. In addition to the obvious variations in the geometry as shown in Table 2, in the chimpanzee there is a lessening in the width of the collagenous area next to the bone approaching the lower lumbar. Also at the upper lumbar area, the lobes appear more rounded than the usual triangular shape.

Consistency of composition, orientation, attachment, etc., appeared throughout the species studied and the vertebral levels. The cross-sectional area, anterior-posterior and lateral dimensions of the ligament increase at lower levels of the spine.

Posterior Longitudinal Ligament (P.L.L.):

Little variation in the ligament composition was noted, and numerous elastic fibers were seen at all levels, increasing in number toward the lower lumbar region. Coarseness of the fiber bundles increased with the size of the vertebral body. The width of the fiber band at the disc edge paralleled the increase in the width of the vertebral body at lower levels of the spine. However, at midline on the vertebral body this trend was reversed, going from a broad band in the cervical area to a fine filament at the lower lumbar level.

Ligament geometry varies with the vertebral geometry. Moving down the spine, the concavity of the posterior surface increased, and the thickness of the ligament at the cartilage end plate diminished due to the greater surface area over which it was spread. The angulation of the fibers toward the lateral aspects, as they approach the disc edge, increased moving down the spine. This was due to the thinning of the ligament at mid-bone and the expansion of the ligament over an ever increasing posterior surface at the disc edge.

Although not observed here, it is reported in the literature (3,18) that the superficial layer of fibers run between three or four vertebrae and the deepest layer extends between adjacent vertebrae.

Anterior Longitudinal Ligament (A.L.L.):

The composition and fiber orientation of this ligament were consistent between vertebral levels and species, although greater amounts of elastic fibers were seen in the chimpanzee. The mode and distribution of attachments were similar, and the thickness of the ligament diminished approaching the lip of the vertebral body due to an increase in fiber bundle compactness.

Obvious geometric changes in the vertebral bodies occur at various levels, and these variances were not quantified here. The body geometry indicated a concavity in the thoracic region greater than at other levels, thus providing a greater area of distribution for fiber attachment.

It is cited in the literature (3,18) but not observed in this report that the most superficial fibers are the longest and extend over three or four vertebrae. The fibers of the intermediate layer span two-to-three vertebrae and those of the inner layer connect adjacent vertebrae.

Supraspinous Ligament (S.S.L.):

The ligamentous structure was similar at all levels and between species, and noteworthy differences were of a gross morphological nature. The ligament was fairly constant in the thickness throughout all levels, but variations occurred between species, the rhesus having the thinnest and the chimpanzee the thickest. The width of the tip of the spinous process changed little throughout the species, but the geometry varied considerably. The surface over which the fibers attach increased at lower levels of the spine. It has been reported by Heyling "that the most superficial fibers of the ligament span three or four vertebrae while the deepest ran between adjacent spines" (5,6).

The cartilage cap ranged from hemispherical to a flattened oval, the latter sometimes showing a slight concavity in the center. The texture of the cap surface seemed to vary microscopically from smooth at the upper levels to rough at the lower levels.

There is some evidence in the literature (5,6,15) that in the lower lumbar region the S.S.L. as described here does not exist. It has been reported that in this lower lumbar region, the S.S.L. becomes a tendinous raphe of the dorsal muscles. In our studies of this structure, few specimens from the lowest lumbar level were observed, as these were utilized in mechanical testing. From the few samples that were observed, evidence of the ligamentous structure was noted.

## CONCLUSION

Random individual variations were noted in nearly all of the general features cited earlier. To establish a statistical significance of the variations from the norm would require extensive quantification and a broader data base. The purpose of this study was not to extensively quantify these features, but morphologically and histologically provide a baseline structural model for concurrent research. In this respect, the histological methods used have established a compositional profile that is remarkably consistent. The profiles have yielded structural models that are being used in mechanical studies of these ligaments. Although statistical analysis has not yet been done, the data project a high confidence level in our compositional models. Such features as fiber orientation, waviness, and size display great consistency. However, before such characteristics can be integrated into a mechanical model with high confidence, a more extensive quantification of variances in these features must be undertaken. To augment the histological studies, biochemical assessments of the composition of these ligaments need to be conducted.

From a morphological and histological standpoint, this report provides substantial information. However, it is hoped that future studies would include quantification of key geometric features, expansion of histological studies to establish points of origin and termination of fibers over several vertebrae, and ultimately the inclusion of human spinal tissue. Although it is expected that significant similarities will exist between human tissue and primate material studied here, caution should be exercised in extrapolating human features from those discerned in this work.

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